# Analysis of Seasonal Thermal Regimes of Selected Aquatic Habitats for Salmonid Populations of Interest to the Okanagan Fish and Water Management Tools (FWMT) Project

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# ANALYSIS OF SEASONAL THERMAL REGIMES OF SELECTED AQUATIC HABITATS FOR SALMONID POPULATIONS OF INTEREST TO THE OKANAGAN FISH AND WATER MANAGEMENT TOOLS (FWMT) PROJECT

by

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# ABSTRACT

Hyatt, K. D. and M. M. Stockwell. 2003. Analysis of seasonal thermal regimes of selected aquatic habitats for salmonid populations of interest to the Okanagan Fish and Water Management Tools (FWMT) project. Can. Manuscr. Rep. Fish. Aquat. Sci. 2618: 26 p

A fish and water management tools (FWMT) project was initiated in 2001 to develop a set of decision support models to improve the basis for seasonal water management decisions that influence annual production variations of sockeye and kokanee salmon (*Oncorhynchus nerka*) in British Columbia's Okanagan Valley. Seasonal changes in water temperature were identified as important driving variables for two FWMT sub-models dealing with predictions of annual production variations for *O. nerka* populations. The absence of long-term (i.e. greater than 5 years), continuous, daily records of water temperature for lake and river mainstem locations within the Okanagan Basin posed a problem for FWMT model development. We examined the feasibility of employing long-term, air temperature records to reconstruct historic seasonal thermal regimes for selected aquatic habitats of special relevance to *O. nerka* production. Short-term records of mean daily, water temperature were assembled for selected aquatic habitats of importance to: (1) beach spawning kokanee in Okanagan Lake, (2) adult sockeye spawning in the Okanagan River downstream of McIntyre Dam and (3) juveniles of both species that rear in Okanagan or Osoyoos Lake habitats. Regression analyses indicated that variations in air temperature alone were sufficient to explain most of the seasonal variations in water temperature at the sites of interest. However, the exact form of the relationships differed significantly among habitat sites (i.e. lake or river) and among seasons (i.e. winter, spring and fall). In Okanagan Lake, seasonal changes in daily water temperature exhibited extreme patterns of hysteresis where aquatic temperatures lagged both spring-summer increases and summer-fall decreases in air temperature. Seasonal patterns of hysteresis were less extreme at Okanagan River mainstem sites. Hysteresis in seasonal, air-versus-water, associations prevented effective application of any single, simple regression relation for annual, air-to-water, temperature reconstructions at lake and river mainstem sites. Mean daily, temperature reconstructions at these sites required the use of (a) a spring-summer, rising-limb function starting the week that the 10-day-mean air temperature (MAT) exceeded 4°C and ending the week that the 10-day MAT was at a maximum, (b) a summer-fall, descending-limb function starting the week that the 10-day MAT was at a maximum and ending the week that the 10-day MAT reached minus 4°C, and (c) a relatively, "flat-limb" function for "winter" initiated when the 10-day MAT dropped below minus 4°C and ending when it increased above 4°C the following spring.

Analyses reported here provide a common foundation for the reconstruction of historic, seasonal water temperature data for application in models of climate variation, river hydrology and fish production variations under assembly by FWMT project participants.

# RÉSUMÉ

Hyatt, K. D. and M. M. Stockwell. 2003. Analysis of seasonal thermal regimes of selected aquatic habitats for salmonid populations of interest to the Okanagan Fish and Water Management Tools (FWMT) project. Can. Manuscr. Rep. Fish. Aquat. Sci. 2618: 26 p

Un projet d'outils de gestion du poisson et de l'eau (OGPE) a été lancé en 2001 pour mettre au point un ensemble de modèles d'aide à la décision visant à améliorer la gestion saisonnière de l'eau qui influe sur la production annuelle du saumon rouge et du kokani (les deux formes d'*Oncorhynchus nerka*) dans la vallée de l'Okanagan, en Colombie-Britannique. Les changements saisonniers de la température de l'eau sont des variables déterminantes de deux sous-modèles OGPE visant à prédire les variations de la production annuelles des populations d'*O. nerka*. Toutefois, l'absence d'enregistrements continus de la température de l'eau effectués à long terme (c.-à-d. pendant plus de cinq ans) à divers sites dans les lacs et le cours d'eau principal du bassin de l'Okanagan pose un problème pour la mise au point des modèles OGPE. Nous avons étudié la possibilité d'utiliser des relevés à long terme de la température de l'air pour reconstituer les régimes thermiques saisonniers passés de certains habitats aquatiques particulièrement importants pour la production d'*O. nerka*. Nous avons compilé les températures de l'eau moyennes quotidiennes relevées à court terme dans certains habitats aquatiques importants pour : (1) le kokani qui fraie sur des plages du lac Okanagan; (2) le saumon rouge adulte qui fraie dans la rivière Okanagan en aval du barrage McIntyre; (3) les saumons rouges et kokanis juvéniles des lacs Okanagan et Osoyoos. Des analyses de régression indiquent que les seules variations de la température de l'air suffisent à expliquer la plupart des variations saisonnières de la température de l'eau aux sites d'intérêt. Toutefois, la forme exacte de la relation varie significativement selon le type d'habitat (lac ou rivière) et la saison (hiver, printemps et automne). Dans le lac Okanagan, les variations saisonnières de la température quotidienne de l'eau présentent une hystérésis très forte : les variations de la température de l'eau sont décalées par rapport aux hausses printanières-estivales et aux baisses estivales-automnales de la température de l'air. Les régimes d'hystérésis saisonniers sont moins marqués dans la rivière Okanagan. L'hystérésis dans les relations saisonnières entre la température de l'air et celle de l'eau empêche d'appliquer efficacement une seule régression simple pour reconstituer la température de l'eau aux sites en question. La reconstitution de la température moyenne quotidienne à ces sites a nécessité l'utilisation de fonctions qui décrivent respectivement : (a) la courbe de montée printemps-été qui débute la semaine où la moyenne décadaire de la température de l'air (MDTA) dépasse 4°C et qui se termine la semaine où la MDTA atteint son maximum; (b) la courbe de descente été-automne qui débute la semaine où la MDTA atteint son maximum et qui se termine la semaine où la MDTA atteint -4°C; (c) la courbe d'hiver relativement plate qui débute lorsque la MDTA passe sous -4°C et qui se termine lorsque la MDTA dépasse 4°C le printemps suivant.

Les analyses présentées dans ce document constituent le fondement de la reconstitution des données passées de température saisonnière de l'eau pour les intégrer dans les modèles des variations du climat, de l'hydrologie fluviale et de la production du poisson qu'élaborent les participants au projet OGPE.

# INTRODUCTION

Okanagan River sockeye salmon are the southerly most distributed stock of this species in Canada. They are the only significant remnant stock of salmon returning to Canada through the Columbia River system in the U.S. Extensive hydroelectric development in both Canada and the U. S., agricultural, urban, recreational and forest land use practices, continued restriction to sub-optimal habitat, water management for flood control and global climate change all pose serious threats to Okanagan sockeye salmon (Chapman et al.1995, Fryer 1995). Long term maintenance of abundance levels sufficient to avoid stock extirpation and to meet First Nations aspirations for harvest in both Canada and the United States continues to be a challenge.

Populations of Okanagan River sockeye salmon (*Oncorhynchus nerka*) and Okanagan Lake kokanee (*O. nerka*) have both experienced declines in recent decades (Hyatt and Rankin 1999, Ashley et al.1998). Annual production variations for both species are influenced significantly by water regulation decisions at a series of low-head, dams built and operated to meet flood control, fisheries and other water use objectives (Anonymous 1954). Water management decisions influence fish production because of their effects on (1) seasonal water level variations at Okanagan Lake beaches where kokanee spawn, (2) discharge, water level and current velocity fields downstream in sections of the Okanagan River where sockeye salmon spawn and (3) water quality of the lake rearing-habitats of both sockeye and kokanee.

During 2001, a project was initiated to develop a set of decision support models to improve the basis for water management decisions that influence annual production variations of these fish. The fish and water management tools (FWMT) project (Hyatt et al. 2001) is an active collaboration among government agencies, First Nations groups and industry. The FWMT project required assembly and analysis of selected physical data to determine historic and predict future impacts of climate and water changes on various life history stages of Okanagan sockeye and kokanee. Long term (>10 years) records of daily water temperature are not readily available for mainstem locations in either Okanagan Lake or the Okanagan River (Stockwell et al. 2001). Here, we examine the feasibility of employing long-term air temperature records to reconstruct historic seasonal thermal regimes for selected aquatic habitats of special relevance to Okanagan kokanee and sockeye salmon production. Analyses reported here, provide a common foundation for the reconstruction of historic, seasonal water-temperature data for application in models of climate variation, river hydrology, and fish production variations under assembly by FWMT project participants.

# METHODS

## DATA SOURCES

### Short Term, Water Temperature - Okanagan Lake and Okanagan River

Stockwell et al. (2001) were not able to identify any long term (i.e. greater than 5 years), continuous daily records of water temperature for any lake or river mainstem locations within the Okanagan Basin. Accordingly, daily water temperature observations generally must be assembled from short term research or resource management projects that provide daily measures for periods lasting weeks or months but rarely one or more full calendar years. Seasonally intermittent, daily temperature records are available from thermograph installations maintained in recent years at several locations in Okanagan Lake and on the Okanagan River. The latter include selected aquatic habitats of importance to: (1) beach spawning kokanee in Okanagan Lake, (2) adult sockeye spawning in the Okanagan River downstream of McIntyre Dam and (3) juveniles of both species that rear in Okanagan or Osoyoos Lake habitats (Figure 1).

Beginning in 1998-99, thermographs have been maintained from October through May at each of three Okanagan Lake beach sites that are important for spawning kokanee (Dave Smith, pers. comm.). Temperature records from these installations were provided to us by provincial Ministry of Water, Land and Air Protection personnel in Penticton (Steve Matthews, unpublished data) for analysis here. In addition, Stockwell et al. (2001) assembled electronic records of thermograph readings for McIntyre and Zosel Dam sites, Okanogan River near Malott, WA, and Okanagan River near VDS 13 (Figure 2). Data for McIntyre, Zosel and Malott locations were received as daily means, maxima and minimums while those from VDS13 were received as hourly temperatures. Temperature records at the McIntyre and Zosel Dam sites were further supplemented with data from published documents (Allen and Meekin 1980, Craddock 1958).

### Long Term, Air Temperature - All Locations

Sockeye and kokanee production variation sub-models, under assembly as part of the FWMT project, required time series, water temperature data for selected aquatic habitats to determine annual incubation, egg hatching and fry emergence dates of kokanee in Okanagan Lake and of sockeye in the Okanagan River. Future success of the FWMT project is to be measured against a historic "base case" of annual sockeye and kokanee production variations over the past 20-30 years (FWMT Workshop, June 2002, Westbank, BC) so the period of interest for reconstruction of seasonal aquatic thermal regimes extends from approximately 1960-1996. Accordingly, time series of daily mean, air temperature records were required for this period in the current analysis.

Environment Canada's Meteorological Services group maintains an archive of climate, hydrographic and water quality data gathered from both active and inactive stations distributed throughout British Columbia and the Yukon (Anonymous 1977). Locations of stations and descriptions of data records at each are available at <http://scitech.pyr.ec.ca/climhydro/> (Environment Canada, Climate, Hydrometric and Water Quality Station Information). Climate stations 1123970-Kelowna A, 1125850-Oscyoos, 1125865-Osoyoos West, 1125760-Oliver, and 1125766-Oliver 2 (Figure 2) were ultimately selected for data retrieval on the basis of the quantity and quality of data available and their proximity to key habitat locations used by one or more life history stages of subject fish stocks. Daily mean, maximum and minimum air temperature observations, for the appropriate periods of record were purchased as electronic files from Environment Canada's Climate Data Services.

## DATA ANALYSIS

Linear regression models have been used in many studies to determine stream temperature on the basis of air temperatures because of the close relationship between the two (Johnson 1971, Crisp and Howson 1982, Pilgrim et al. 1988, Webb and Nobilis 1997, Kyle and Brabets 2001). In addition, linear regression models of air versus water temperature are attractive for both retrospective and prospective studies of climate variation effects because air temperature is the only input variable required and General Circulation Models (GCM's) simulate this variable better than other climate variables. Because daily mean, water temperatures (i.e. short time scale measures) were the focus of interest in the current study, we expected that the best predictive relations would exist for associations between water temperature and multi-day, mean air temperatures (Crisp and Howson 1982, Stefan and Preud'homme 1993). Consequently, we tested for significant associations between daily mean, water temperatures and a series of multi-day mean air temperatures starting with the mean of air temperature between day n and day n-1 and extending to the mean of air temperature between day n and day n-20.

Development of air-water temperature relations based on short term data sets for both air and water temperature, was anticipated to permit reconstruction of historic aquatic thermal regimes for selected aquatic habitats on the basis of long-term, air temperature records alone. Application of such relationships implicitly assumes that there have been no significant changes in the geology, hydrology or biology of the subject ecosystems capable of significantly altering the key processes of air-to-water heat exchanges in the Okanagan Valley (e.g. removal of forest canopy, major alterations in seasonal exchanges between surface and groundwater sources, etc...). Agricultural development, major alterations of the Okanagan River mainstem for flood control and "forest canopy" removal from the Okanagan River riparian zone all predate the 1960-1999 period of interest for thermal regime reconstruction considered here (Stockner and Northcote 1974). Therefore, we assume that the general assumption of conservative, heat exchange processes between atmosphere and hydrosphere elements have been met here.

## RESULTS AND DISCUSSION

Water temperature observations considered here originate from sites (Figure 2) representing Okanagan Lake and River habitats of importance for spawning by adult kokanee (Okanagan Lake beaches, Andrusak et al.2002, Dill 1996), spawning by adult sockeye (McIntyre Dam, Hyatt and Rankin 1999), return migrations by adult sockeye (Malott, WA, Zosel Dam and Okanagan River, Major and Mighell 1966) or lake rearing by juveniles of both species (Okanagan Lake, Ashley et al.1998; Osoyoos Lake and Zosel Dam, Hyatt and Rankin 1999, Rankin et al. 1998, 2001 and Wright 2002). The period of record varied greatly from site to site such that some sites provided fewer than 100 observations of daily temperature (Osoyoos Lake stations) while others yielded more than 1000 (Okanagan River at McIntyre Dam, Okanagan River at Zosel Dam). In general, single linear regressions were inadequate to account for site-specific seasonal variations of air versus water temperature. However, season and site-specific relationships were much stronger (see details below). As anticipated, multi-day means of air temperature provided better fits to daily mean, water temperatures than single observations. Statistically significant associations were found for most seasonal air-to-water data sets for all mean air temperature (MAT) variables tested from the 2-day MAT to the 20-day MAT. The 10-day mean air temperature (10-day MAT) provided an equivalent or superior performance for the greatest number of data sets considered here. Therefore, for brevity, results reported below are restricted to those associated with the 10-day MAT alone.

### AIR VERSUS SURFACE WATER TEMPERATURES FOR OKANAGAN LAKE

Mean daily water temperatures from 3 Okanagan Lake sites (OKLsoutheast, OKLnortheast, OKLnorthwest) were routinely assessed between 1996 and present. The seasonal period of water temperature assessment at these sites coincides with the annual fall-to-spring interval during which eggs of beach spawning kokanee salmon (*O. nerka*) undergo incubation, hatching and fry emergence there. During the kokanee incubation period, mean daily water temperatures are closely associated with air temperature during some seasonal intervals but not others. Observations from OKLse during 2000-2001 (Figure 3) illustrate the typical pattern of seasonal change. The kokanee incubation period starts with the "fall" interval when Okanagan Lake is substantially warmer than the surrounding air but both the air and water exhibit similar, average rates of cooling (Figure 3, Oct -Dec). The "winter" interval is next when lake surface temperatures are largely unresponsive to multi-day changes in air temperature (Figure 3, Dec-Feb) and ends with a "spring" interval during which both air and lake temperatures warm rapidly (Figure 3, Mar-May). The observed pattern of extreme hysteresis (i.e. variable delays between air versus water temperature changes among fall, winter and spring) is related to the complex physics of air-water, heat-exchange processes. These involve evaporative cooling of the lake in the late summer-to-fall, thermal destratification in the fall-to-winter; rapid, wind-induced, mixing of surface and deep waters through the winter and initiation of thermal stratification and evaporative cooling once again in the spring-to-summer. The large surface area and volume of

Okanagan Lake has a major influence on all of these processes (Blanton and Ng 1972, Blanton 1973, Stockner and Northcote 1974).

Aquatic habitats exhibiting extreme patterns of hysteresis in air-water, temperature relationships such as those observed in Okanagan Lake are poor candidates for the use of single, regression models to predict seasonal changes in water temperature. Thus, although the association between changes in daily mean water temperature at OKLse and the 10-day-mean, air temperature (MAT) in Kelowna was highly significant ($p < 0.001$), the relationship for pooled daily observations accounted for less than half of the variance in the data ($r^2 = 0.45$) and exhibited large seasonal biases (Figure 4). The regulation of the physical dynamics of lakes is governed largely by differences in the density of water molecules that have the peculiar property of reaching maximum density at 3.94 °C (Wetzel 1975). The "density differences per degree lowering" (Vallentyne 1957) increase markedly as the temperature moves either above or below 4 °C. Because physical work is required to mix fluids of differing density, the amount of work required to mix layered (i.e. stratified) water masses between 24 °C and 25 °C is 30 times that required for the same masses between 4 °C and 5 °C (Wetzel 1975). Deviations from the temperature of maximum density, either cooling below or warming above 4 °C, result in very small changes in density differences per change in temperature. Thus, at temperatures around 4 °C there is relatively little thermal resistance to mixing, and only small amounts of wind energy are required to mix surface waters deep into the water column.

In Okanagan Lake, surface water temperatures generally cool to 4 °C in the fall-winter interval at about the time that 10-day-MAT's reach minus 4 °C. In the winter-spring interval, surface water temperatures reach or exceed 4 °C by the time that 10-day-MAT's reach 4 °C. Consequently, we elected to define three seasonal air-water temperature intervals (winter, spring and fall) based on winter-spring and fall-winter cut-off points when 10-day-MAT's achieved plus 4 °C and minus 4 °C respectively. This classification nicely separated the air versus water temperature observations into three data clusters exhibiting only a minor overlap (Figure 5). Analysis of these data clusters provided large improvements in the amount of variance accounted for by simple linear regressions of mean daily water temperatures versus 10-day-MAT's for the spring and fall intervals ($r^2$ values $> 0.80$ and $p < 0.001$ at all sites, Figure 6 a, b and Table 1). However, winter changes in water temperature are relatively unresponsive to even large changes in air temperature (Figure 6 c and Table 1: $r^2 = < 0.05$ and $p > 0.05$).

We briefly examined the use of a non-linear regression model based on the logistic function (Mohseni et al. 1998, Mohseni and Stefan 1999) as an alternative to predicting water temperature on the basis of the season-specific, regression sets above. However, hysteresis patterns for Okanagan Lake air-water temperature observations were extreme enough to require separate fits of the logistic function to the winter spring and fall-winter combinations of data. Because the logistic function offered no improvement in performance over the seasonal regressions, it was not considered further here.

## AIR VERSUS SURFACE WATER TEMPERATURES FOR OKANAGAN RIVER AT MCINTYRE DAM

Water temperatures have been recorded routinely at McIntyre Dam (McID) in recent years in association with projects by the Okanagan Nation Fisheries Commission and Canada's Department of Fisheries and Oceans to rebuild Okanagan sockeye salmon. Spawning by Okanagan sockeye is concentrated in a natural segment of the Okanagan River extending from just below McIntyre Dam to approximately 5 km down river (Hyatt and Rankin 1999). Accordingly, temperature changes recorded at the McID site reflect seasonal changes in the thermal environment that sockeye adults, eggs and fry experience on the spawning grounds. Records of daily water temperature have been commonly obtained at McIntyre Dam during the Sept-to-May spawning and egg incubation interval. However, full-year coverage of seasonal water temperatures is generally absent. Assessments of water temperature at McID provided almost full-year coverage in 1997, which exhibited the familiar pattern of delayed warming and cooling of the Okanagan River mainstem relative to daily changes in air temperature recorded at Oliver (Figure 7).

Examination of all daily, mean water temperature records versus the 10-day-MAT from Oliver indicates a clear but less extreme pattern of seasonal hysteresis for water versus air temperatures at McID relative to the Okanagan Lake stations (Figure 8). Similarly, regression analysis, following clustering of the data into spring, fall and winter intervals, provided a set of relationships that account for over 95 % of the variance in the relation between daily mean, water temperatures and 10-day-MAT values for spring and fall but not the winter interval (Figure 9a, b, c and Table 1). The lag between air temperature and water cooling in the late summer is undoubtedly influenced by the "heat reservoir" effect of the string of lakes including Okanagan (26 km upstream), Skaha (11km upstream), and Vaseux lakes (0.25 km upstream) through which water approaches McIntyre Dam (Figure 1). Winter water temperatures in Okanagan Lake appeared to be unresponsive to changes in air temperature. By contrast, daily mean water temperatures in winter at McID exhibit a highly significant and persistent relationship with 10-day-MAT's ($p < 0.001$, $r^2 = 0.63$, Table 1 and Figure 9c). Thus, although the string of lakes upstream of McID are certain to exhibit a thermal buffering effect over winter water temperatures at McID, it is not strong enough to overwhelm the influence of local air temperature on water temperatures in the Okanagan River mainstem.

## OSOYOOS LAKE SURFACE TEMPERATURES AND TEMPERATURE AT ZOSEL DAM

There are virtually no consecutive day temperature measurements for Osoyoos Lake. However, mean daily water temperature observations have been recorded at Zosel Dam at the outlet to Osoyoos Lake and these are closely associated (Figure 10, $r^2 = 0.94$, $p < 0.001$, $n = 51$, data from Stockwell et al. 2001) with spot measures of surface temperature taken in various basins of the lake over several years of time. Given that same-day, temperatures for the Zosel and Osoyoos sites are

indistinguishable, mean daily water temperatures measured at Zosel Dam will serve as a reliable indicator of seasonal changes in temperature that juvenile sockeye salmon would encounter in the surface waters of Osoyoos Lake.

## WATER TEMPERATURE AT MCINTYRE DAM AND AT ZOSEL DAM

Water temperature observations recorded over several years at Zosel Dam provide better coverage for the spring-to-summer interval while coverage is best at McIntyre Dam for the fall-to-winter interval. Same-day measurements of mean daily water temperatures at both McIntyre and Zosel dams are very closely associated (Figure 11, $r^2 = 0.97$, $p < 0.001$, $n = 222$, data from Stockwell et al.2001). However, the majority of observations in the relationship fall above the 1:1 line such that water temperatures at Zosel Dam are consistently about 1°C higher than those at McIntyre. Thus, if a 1°C adjustment is made to McIntyre water temperatures, we suggest that either daily water temperature measurements at McID or predictions that employ the McID air-to-water relationship will suffice to estimate seasonal variations for surface water temperatures in Osoyoos Lake or of Okanagan River temperatures in Washington State at Zosel Dam. The close association between water temperatures at McIntyre Dam, Osoyoos Lake and Zosel Dam is not surprising given the close proximity of all three sites (Figure 1) and the fact that water exiting both McIntyre Dam and Zosel Dam consists of surface spill from small lakes (i.e. Vaseux and Osoyoos lakes respectively, Figure 1). Blanton (1973) noted that small lakes such as Skaha and Osoyoos in the south Okanagan tend to exhibit seasonal surface temperatures that on average differ by less than 1.5 °C.

## WATER TEMPERATURE AT MCINTYRE DAM AND AT MALOTT, WASHINGTON

The Okanagan River flows a distance of approximately 120 km from Zosel Dam before it reaches its confluence with the Columbia River in Washington State (Figure 1). The Okanagan River receives significant additions of water from several tributaries along the way. Some of these tributaries originate at higher elevations and lack major lakes such that their snow-fed waters have lower temperatures than those of the Okanagan mainstem at either McIntyre or Zosel. For example, the Similkameen River exhibits mean daily water temperatures that are several degrees lower than those of the Okanagan mainstem at Zosel (Stockwell et al.2001). Thus, temperatures that adult sockeye encounter during migration up the Okanagan River at its confluence with the Columbia River may be somewhat lower than those encountered in the mainstem at Zosel. Comparison of same-day temperatures at either McIntyre or Zosel Dams with those recorded 120 km downstream at Malott, WA suggest there is no readily identifiable difference when seasonal water temperatures are below 20 °C (Figure 12 a, b). However, when regional water temperatures rise above 20°C, water temperatures at Malott diverge from those observed upstream at either McIntyre or Zosel such that the latter exhibit daily water temperatures that range from 1-5 °C warmer than those observed at Malott. We attribute these differences to predictable seasonal increases of water inputs from cooler, snow-fed tributaries to the Okanagan River and especially the Similkameen River. The magnitude of summer-fall

temperature differences between Malott and upstream locations at Zosel and McIntyre are sufficient to influence the migratory behaviour of adult sockeye (references in Hodgson and Quinn 2002).

## CONCLUSIONS

(1) The FWMT project requires assembly and analysis of selected, physical-variable data to determine historic and predict future impacts of climate and water changes on various life history stages of Okanagan sockeye and kokanee.

(2) Long term (>5 years) records of daily water temperature are not readily available during the period of interest (1960-1999) for mainstem lake or riverine habitats of importance to various life history stages of salmonid fishes in the Okanagan Basin.

(3) Regression analyses indicate that variations in air temperature alone are sufficient to explain most of the seasonal variations in water temperature at the sites of interest. However, the exact form of the relationships differed significantly among lake and riverine habitat sites. Water-to-water, relationships are also available to serve as "transfer function" predictors of water temperature for some site-pairs.

(4) In Okanagan Lake, seasonal changes in daily water temperature exhibit extreme patterns of hysteresis where aquatic temperatures lag both spring-summer increases and summer-winter decreases in air temperature due to the complex physics of air-water, heat exchanges. Seasonal patterns of hysteresis are less extreme at Okanagan River mainstem sites than in Okanagan Lake.

(5) Pronounced patterns of hysteresis in seasonal, air-versus-water, associations prevented effective application of any single, simple regression relation for annual, air-to-water temperature reconstructions at lake and river mainstem sites. Daily mean, temperature reconstructions at these sites require the use of season-specific, regression functions that represent:

1. a spring-summer, rising-limb function starting the week that the 10-day MAT exceeds 4 °C and ending the week that the 10-day MAT is at a maximum,
2. a summer-fall, descending-limb function starting the week that the 10-day MAT is at a maximum and ending the week that the 10-day MAT reaches minus 4 °C and
3. a relatively "flat-limb", function for "winter" initiated when the 10-day MAT drops below minus 4 °C and ending when it increases above 4 °C the following spring.

(6) Regression relationships recommended for reconstruction of daily mean, water temperatures and seasonal thermal regimes of relevance to various life history stages of salmonids of interest to the FWMT Project are summarized in Table 2 (see text for details).

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Table 1. A summary of regression relationships developed for reconstructing mean daily water temperatures and seasonal thermal regimes for life history stages of kokanee and sockeye salmon in mainstem lake and riverine habitats of the Okanagan Basin.

| **Regressions by life history stage, temporal interval, and location** | $r^2$ | *p* | *n* |
|---|---|---|---|
| Kokanee Spawning and Egg Incubation – Okanagan Lake Southeast (OKLse) | | | |
| (1) Daily all year surface temperature of OKLse = 0.47 x (10-day MAT at Kelowna) + 5.69 | 0.45 | < 0.001 | 802 |
| (2) Daily spring temperature of OKLse = 0.75 x (10-day MAT at Kelowna) + 1.31 | 0.80 | < 0.001 | 152 |
| (3) Daily fall temperature of OKLse = 0.87 x (10-day MAT at Kelowna) + 6.26 | 0.86 | < 0.001 | 317 |
| (4) Daily fall temperature of OKLse (when 10-day MAT > 0 °C) = 0.99 x (10-day MAT at Kelowna) + 5.64 | 0.83 | < 0.001 | 253 |
| (5) Daily fall temperature of OKLse (when 10-day MAT ≤ 0 °C) = 0.71 x (10-day MAT at Kelowna) + 6.59 | 0.42 | < 0.001 | 64 |
| (6) Daily winter temperature of OKLse = - 0.003 x (10-day MAT at Kelowna) + 4.44 | 0.0004 | = 0.70 | 331 |
| (7) Note: daily mean water temperature through the winter interval at OKLse = 4.4 °C | | | |
| Kokanee Spawning and Egg Incubation – Okanagan Lake Northeast (OKLne) | | | |
| (8) Daily all year surface temperature of OKLne = 0.49 x (10-day MAT at Kelowna) + 5.85 | 0.45 | < 0.001 | 589 |
| (9) Daily spring temperature of OKLne = 0.77 x (10-day MAT at Kelowna) + 1.65 | 0.72 | < 0.001 | 113 |
| (10) Daily fall temperature of OKLne = 0.92 x (10-day MAT at Kelowna) + 6.38 | 0.81 | < 0.001 | 240 |
| (11) Daily fall temperature of OKLne (when 10-day MAT > 0 °C) = 1.11 x (10-day MAT at Kelowna) + 5.49 | 0.75 | < 0.001 | 189 |
| (12) Daily fall temperature of OKLne (when 10-day MAT ≤ 0 °C) = 0.57 x (10-day MAT at Kelowna) + 6.42 | 0.30 | < 0.001 | 51 |
| (13) Daily winter temperature of OKLne = 0.034 x (10-day MAT at Kelowna) + 4.63 | 0.04 | > 0.001 | 236 |
| (14) Note: daily mean water temperature through the winter interval at OKLne = 4.7 °C | | | |
| Kokanee Spawning and Egg Incubation – Okanagan Lake Northwest (OKLnw) | | | |
| (15) Daily all year surface temperature of OKLnw = 0.47 x (10-day MAT at Kelowna) + 5.85 | 0.42 | < 0.001 | 589 |
| (16) Daily spring temperature of OKLnw = 0.81 x (10-day MAT at Kelowna) + 1.16 | 0.70 | < 0.001 | 113 |
| (17) Daily fall temperature of OKLnw = 0.87 x (10-day MAT at Kelowna) + 6.70 | 0.84 | < 0.001 | 240 |
| (18) Daily fall temperature of OKLnw (when 10-day MAT > 0 °C) = 1.003 x (10-day MAT at Kelowna) + 6.103 | 0.76 | < 0.001 | 189 |
| (19) Daily fall temperature of OKLnw (when 10-day MAT ≤ 0 °C) = 0.43 x (10-day MAT at Kelowna) + 6.42 | 0.39 | < 0.001 | 51 |
| (20) Daily winter temperature of OKLnw = 0.012 x (10-day MAT at Kelowna) + 4.52 | 0.003 | = 0.40 | 234 |
| (21) Note: daily mean water temperature through the winter interval at OKLnw = 4.5 °C | | | |

Table 1 (cont'd)

| Regressions by life history stage, temporal interval, and location | $r^2$ | $p$ | $n$ |
|---|---|---|---|
| Sockeye Spawning & Egg Incubation - Okanagan River at McIntyre Dam (McID) | | | |
| (22) All year daily mean temperature at McID = 0.88 x (10-day MAT at Oliver) + 1.98 | 0.92 | < 0.001 | 1,249 |
| (23) Daily spring temperature at McID = 1.07 x (10-day MAT at Oliver) - 1.87 | 0.96 | < 0.001 | 434 |
| (24) Daily fall temperature at McID = 0.87 x (10-day MAT at Oliver) + 3.18 | 0.97 | < 0.001 | 487 |
| (25) Daily fall temperature at McID (when 10-day MAT > 0 °C) = 0.87 x (10-day MAT at Oliver) + 3.23 | 0.96 | < 0.001 | 461 |
| (26) Daily fall temperature at McID (when 10-day MAT ≤ 0 °C) = 0.72 x (10-day MAT at Oliver) + 2.83 | 0.40 | < 0.001 | 26 |
| (27) Daily winter temperature at McID = 0.20 x (10-day MAT at Oliver) + 1.74 | 0.63 | > 0.001 | 277 |
| Juvenile Sockeye Rearing - Osoyoos Lake | | | |
| (28) Daily surface temperature of Osoyoos Lake = 1.04 x (daily MWT at ZD) - 0.87 | 0.94 | < 0.001 | 52 |
| (29) Daily mean water temperature at Zosel Dam = 0.95 x (daily MWT at McID) + 1.84 | 0.97 | < 0.001 | 222 |
| Adult Sockeye Migration - Okanogan River at Zosel Dam (ZD) | | | |
| (30) Daily spring water temperature at ZD = 0.97 x (10-day MAT at Oliver) + 1.62 | 0.89 | < 0.001 | 1,161 |
| (31) Daily fall water temperature at ZD = 1.05 x (10-day MAT at Oliver) + 1.94 | 0.65 | < 0.001 | 20 |
| (32) Daily winter water temperature at ZD = 0.16 x (10-day MAT at Oliver) + 1.37 | 0.04 | = 0.3 | 43 |
| Adult Sockeye Migration - Okanogan River at Malott, WA | | | |
| (33) Daily mean water temperature at Malott = 0.80 x (daily MWT at ZD) + 2.04 | 0.87 | < 0.001 | 256 |
| (34) Daily mean water temperature at Malott = 0.86 x (daily MWT at McID) + 1.27 | 0.93 | < 0.001 | 163 |

Table 2. Recommended regressions for reconstructing thermal regimes for specific life history stages of kokanee and sockeye salmon of interest to the FWMT Project.

| Life History Stage, Species, Location & Time | $r^2$ | $p$ | $n$ |
|---|---|---|---|
| Spawning and Egg Incubation of Kokanee - Okanagan Lake Southeast (OKLse) | | | |
| (1) Daily fall temperature of OKLse = 0.87 x (10-day MAT at Kelowna) + 6.26 | 0.86 | < 0.001 | 317 |
| (2) Winter (mean of daily temp. for entire interval) = 4.4 °C | na | na | 331 |
| (3) Daily spring temperature of OKLse = 0.75 x (10-day MAT at Kelowna) + 1.31 | 0.80 | < 0.001 | 152 |
| Spawning and Egg Incubation of Kokanee - Okanagan Lake Northeast (OKLne) | | | |
| (4) Daily fall temperature of OKLne = 0.92 x (10-day MAT at Kelowna) + 6.38 | 0.81 | < 0.001 | 240 |
| (5) Winter (mean of daily temp. for entire interval) = 4.7 °C | na | na | 236 |
| (6) Daily spring temperature of OKLne = 0.77 x (10-day MAT at Kelowna) + 1.65 | 0.72 | < 0.001 | 113 |
| Spawning and Egg Incubation of Kokanee - Okanagan Lake Northwest (OKLnw) | | | |
| (7) Daily fall temperature of OKLnw = 0.87 x (10-day MAT at Kelowna) + 6.70 | 0.84 | < 0.001 | 240 |
| (8) Winter (mean of daily temp. for entire interval) = 4.5 °C | na | na | 234 |
| (9) Daily spring temperature of OKLnw = 0.81 x (10-day MAT at Kelowna) + 1.16 | 0.70 | < 0.001 | 113 |
| Kokanee Rearing - Okanagan Lake (all stations pooled by season) | | | |
| (10) Daily fall temperature of Okanagan Lake = 0.88 x (10-day MAT at Kelowna) + 6.44 | 0.83 | < 0.001 | 797 |
| (11) Winter (mean of daily temp. for entire interval) = 4.5 °C | na | na | 803 |
| (12) Daily spring-summer temperature of Okanagan Lake = 0.78 x (10-day MAT at Kelowna) + 1.30 | 0.74 | < 0.001 | 378 |
| Sockeye Spawning and Egg Incubation - Okanagan River at McIntyre Dam (McID) | | | |
| (13) Daily fall temperature at McID = 0.87 x (10-day MAT at Oliver) + 3.18 | 0.97 | < 0.001 | 487 |
| (14) Daily winter temperature at McID = 0.20 x (10-day MAT at Oliver) + 1.74 | 0.63 | < 0.001 | 277 |
| (15) Daily spring temperature at McID = 1.07 x (10-day MAT at Oliver) - 1.87 | 0.96 | < 0.001 | 434 |
| Juvenile Sockeye Rearing - Osoyoos Lake | | | |
| (16) Daily spring-summer temperature at McID = 1.07 x (10-day MAT at Oliver) - 1.87 | 0.96 | < 0.001 | 434 |
| (17) Daily fall-winter temperature at McID = 0.87 x (10-day MAT at Oliver) + 3.18 | 0.97 | < 0.001 | 487 |
| Migrating sockeye - Okanogan River at Zosel | | | |
| (18) Daily spring-fall temperature at ZD = 0.97 x (10-day MAT at Oliver) + 1.62 | 0.89 | < 0.001 | 1,161 |
| Migrating sockeye - Okanogan River at Malott | | | |
| (19) Daily spring-fall temperature at Malott = 0.80 x (daily MWT at Zosel) + 2.04 | 0.87 | < 0.001 | 256 |

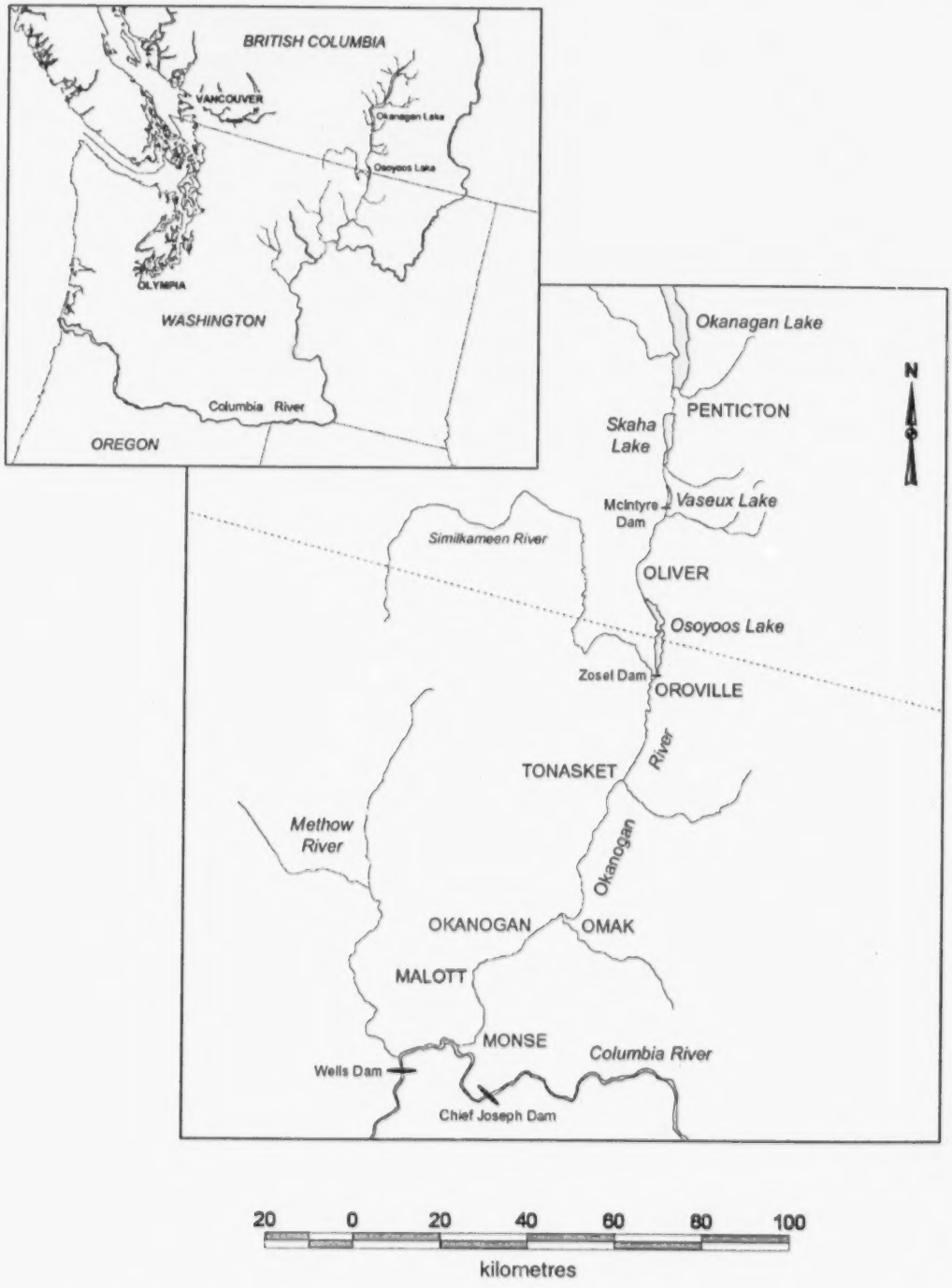



Figure 1. General location of the Canada-U.S. study area for the Fish and Water Management Tools (FWMT) Project.

Figure 2. Location of (a) climate stations maintained by Canadian (Environment Canada) and U. S. agencies (National Oceanic and Atmospheric Administration) in the study area and of (b) aquatic habitat sites providing short term, observations of daily water temperature.

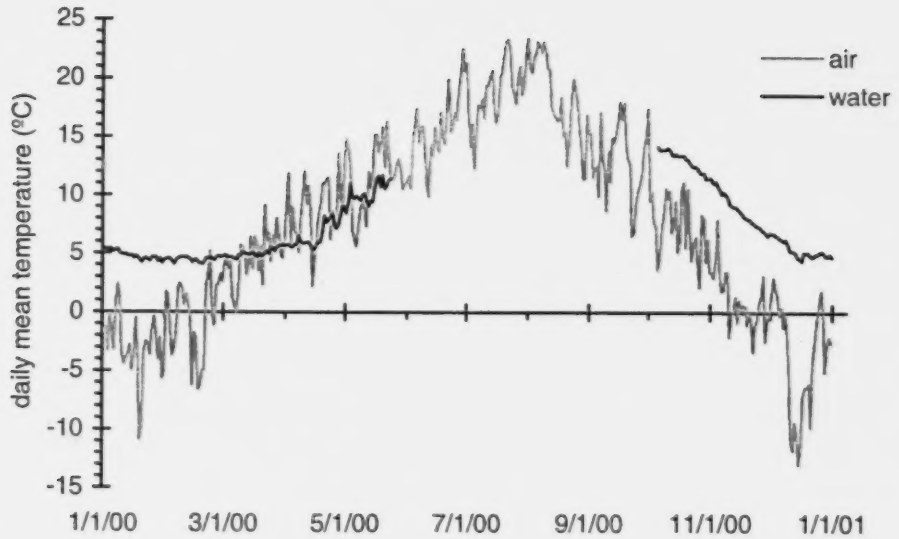



Figure 3. A comparison of seasonal changes in mean daily air temperatures in Kelowna (Station 1123970, Kelowna A) versus water temperature at beach spawning sites for kokanee in the southeast portion of Okanagan Lake (OKLse) from January 2000 to January 2001.

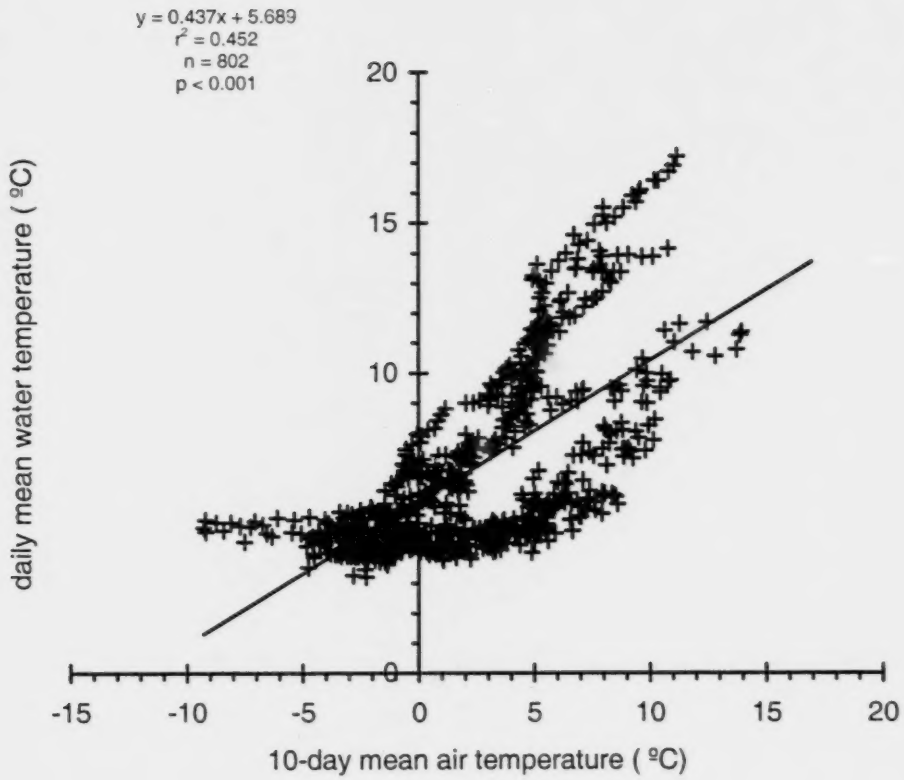



Figure 4. Relationship between the 10-day mean of air temperature at Station 1123970, Kelowna A and the daily means of water temperature recorded at beach spawning sites for kokanee in the southeast portion of Okanagan Lake from October to May for the years 1998 through 2002.

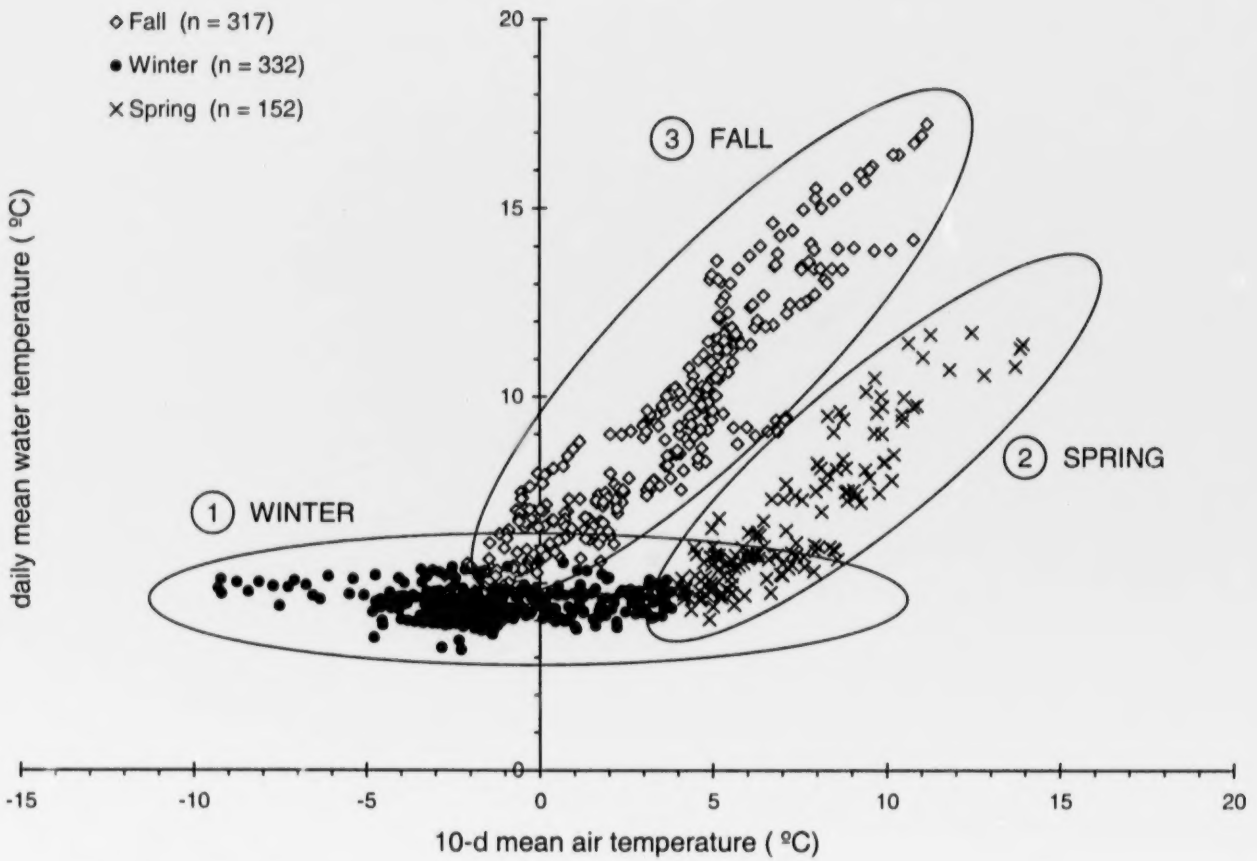



Figure 5. Classification of "winter, spring and fall" clusters of air-water, temperature observations according to seasonal cut-off points applied to the Okanagan Lake southeast data set. Winter-spring and fall-winter cut-off points occur when 10-day-mean air temperatures (MAT) achieve either plus 4°C or minus 4°C respectively. The summer separation point between the spring and fall series occurs when 10-day MAT's achieve the seasonal maximum for a given observation set. Note the pattern of extreme hysteresis in seasonal air-water temperature relationships (see text for explanation)

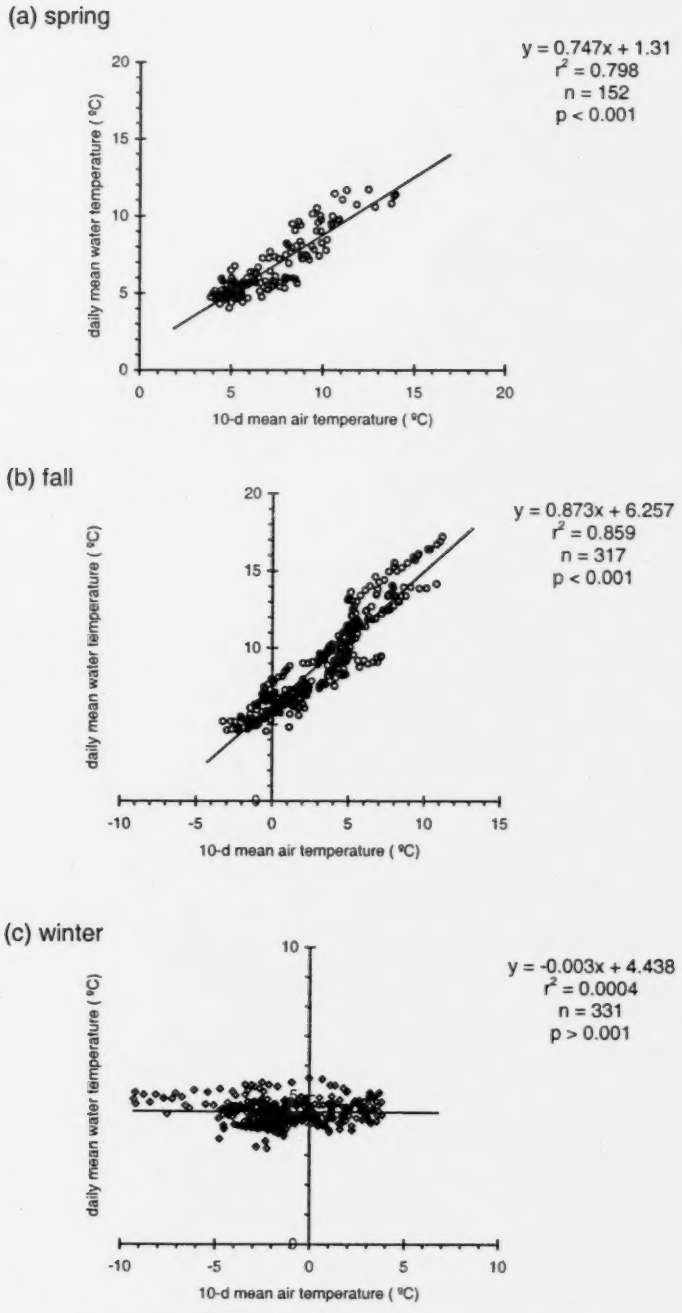



Figure 6. Relationship between the 10-day mean of air temperature at Station 1123970, Kelowna A and the daily mean, water temperature recorded at Okanagan Lake southeast for (a) spring, (b) fall and (c) winter intervals from October 1998 to May 2002 . Additional results of regression analyses for OKLse, OKLne and OKLnw are summarized in Table 1.

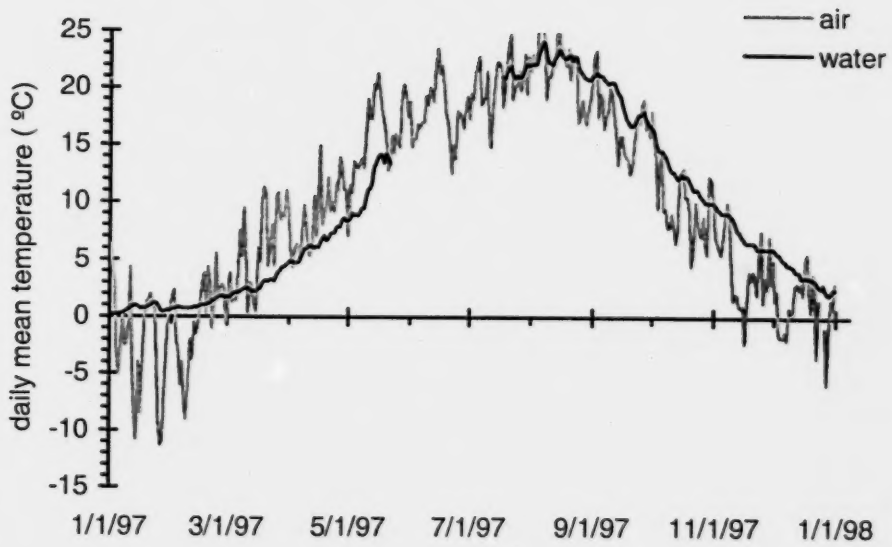



Figure 7. A comparison of seasonal changes in daily mean, air temperatures in Station 1125766, Oliver versus water temperatures recorded from January 1997 to January 1998 at McIntyre Dam (McID). Temperatures at the latter site are considered representative of those experienced by sockeye salmon adults, eggs and fry at spawning sites immediately downstream of McID in the Okanagan River mainstem.

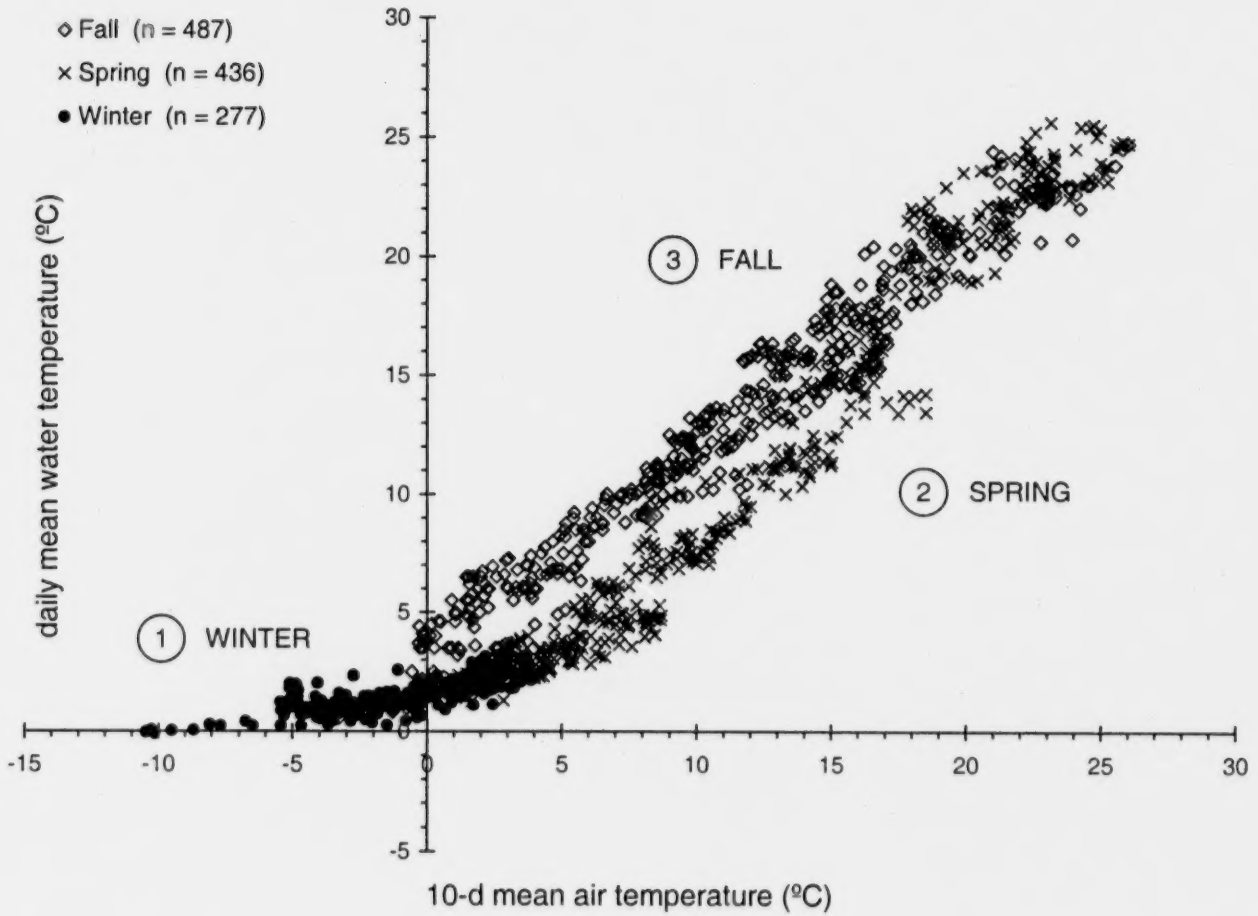



Figure 8. Classification of "winter, spring and fall" clusters of air-water, temperature observations according to seasonal cut-off points applied to the McIntyre Dam data set. See text and legend in Figure 5 for seasonal interval start and end point criteria.

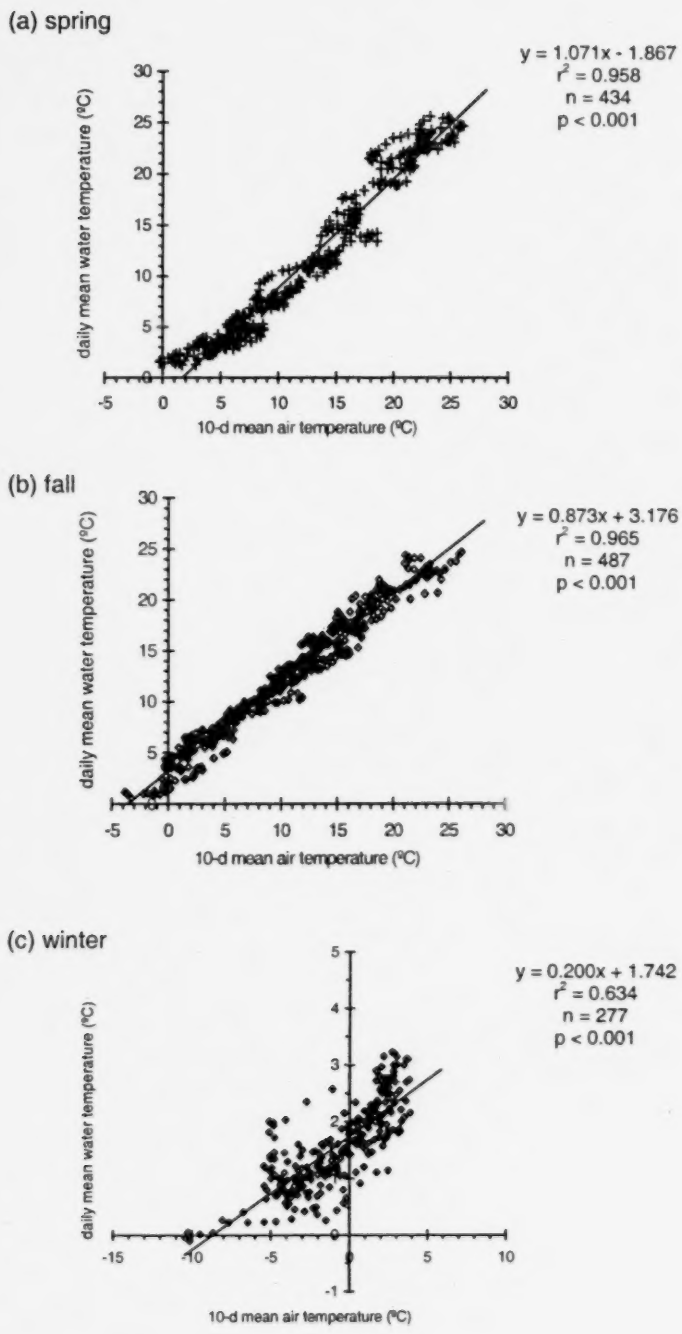



Figure 9. Relationship between the 10-day-mean of air temperature at Oliver and the daily mean, water temperatures recorded at McIntyre Dam for (a) spring, (b) fall and (c) winter intervals. Data sources are fully documented in Stockwell et al. (2001). See Table 1 for additional results of regression analyses for seasonal interval observations at McID.

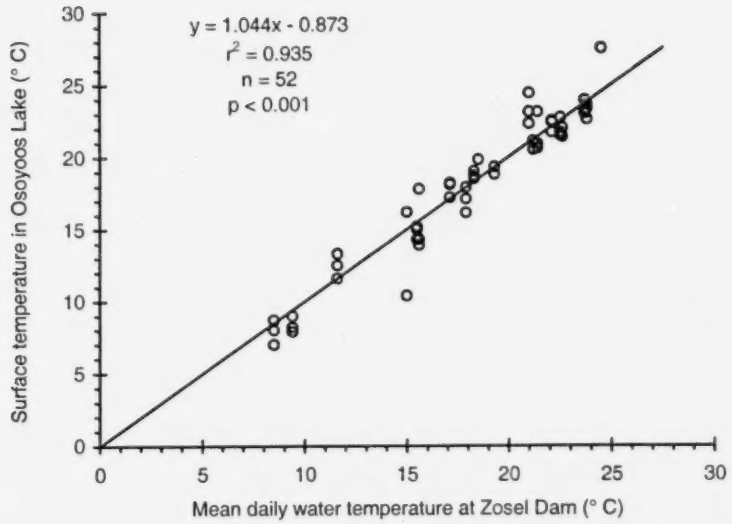



Figure 10. Relationship between daily mean, water temperatures measured in the north, south or central basins for the surface waters of Osoyoos Lake and Okanagan River temperatures recorded at the Zosel Dam outlet of Osoyoos Lake. The 1:1 line is shown on the figure while the equation describes the line of best fit to the data.

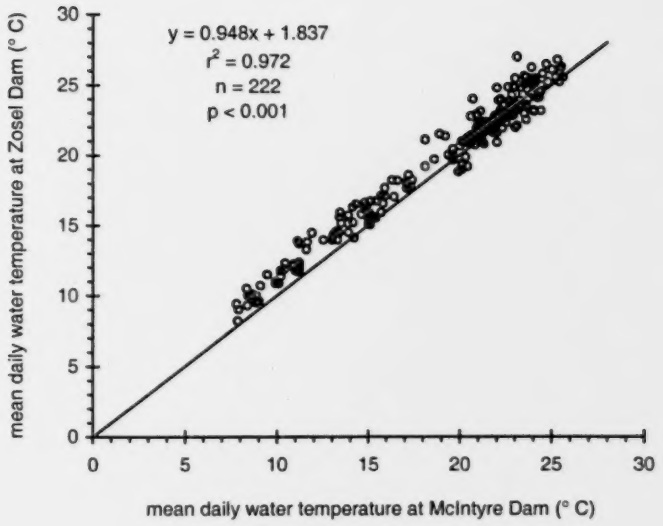
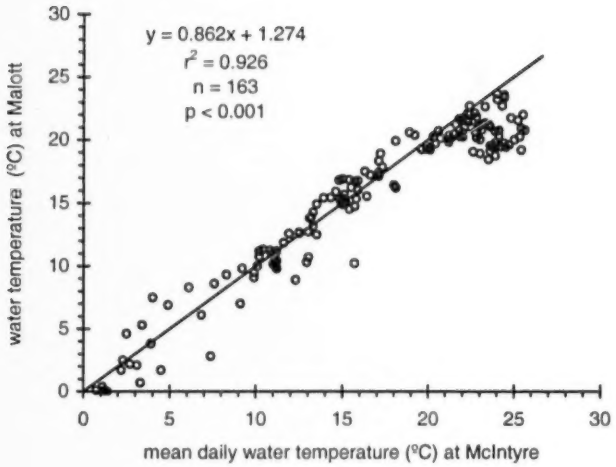



Figure 11. Relationship between daily mean, water temperatures for the Okanagan River mainstem at McIntyre Dam, B. C. and Okanagan River temperatures recorded for the outlet of Osoyoos Lake at Zosel Dam, Washington. The 1:1 line is shown on the figure while the equation describes the line of best fit to the data.

(a)




(b)

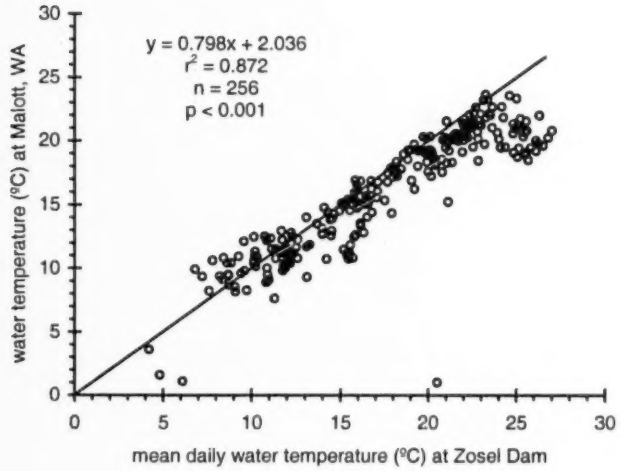



Figure 12. Relationship between daily mean, water temperatures for the Okanagan River mainstem at (a) McIntyre Dam, B.C. versus a location approximately 120 km downstream at Malott, Washington, and (b) at Zosel Dam versus Malott, WA. The 1:1 lines are shown on figure panels while the equations describe the lines of best fit to the data.